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Soil Microbial Biomass and Mineralizable Carbon of Water-Stable Aggregates

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ABSTRACT

Biophysical alterations of agricultural soils following adoption of zero tillage (ZT) deserve investigation in order to better understand the processes of soil organic C (SOC) sequestration and turnover. We determined the vertical distribution of soil microbial biomass C (SMBC), C mineralized in 24 d under standard conditions, and basal soil respiration (BSR) in five water-stable aggregate classes. Four soils (loam, silt loam, clay loam, and clay) from the Peace River region of northern Alberta and British Columbia were sampled following 4 to 16 yr under comparison of conventional shallow tillage (CT) and ZT. Macroaggregates (>0.25 mm) had greater SMBC, more C mineralized in 24 d, and higher BSR than microaggregates at a depth of 0 to 50 mm. Differences between macro- and microaggregates in these properties decreased with soil depth. Carbon mineralized in 24 d and SMBC were 9 ± 9% greater (mean of four soils ± standard deviation among soils) under ZT than under CT in macroaggregates, but were 6 ± 11% lower in whole soil due to lower amounts in microaggregates under ZT than under CT. Macroaggregate-protected SOC to a depth of 200 mm was 6.7 ± 1.9 g m^{-2} under CT and 9.8 ± 2.6 g m^{-2} under ZT. Soil organic C in macroaggregates, which had high concentrations of active pools of SOC, appeared to have been shunted into the more stable microaggregate fraction after disturbance with CT. Unlike in temperate, humid climates, decomposition of SOC during the passage from macro- to microaggregates may have been limited by the frigid, semiarid climate.

KNOWLEDGE of SOC sequestration and turnover is important in understanding biogeochemical cycles, land management effects on soil quality, and the contribution of soils to greenhouse gas emissions. Soil microbial biomass and mineralizable C are active pools of SOC that are more sensitive to early changes in SOC turnover due to alterations in land management than total SOC content (Powlson et al., 1987).

Cultivated land in the Great Plains of North America has lost 25 to 60% of the organic matter present under native grassland (Haas et al., 1957; Campbell and Souster, 1982) although levels appeared to have stabilized after the first few decades of rapid loss. For example, on a sandy loam in Colorado, 95% of the loss of SOC and mineralizable C due to cultivation of grassland occurred within the first decade (Bowman et al., 1990). Loss of SOC following cultivation of native grassland soils has been attributed to the destruction of macroaggregates and subsequent mineralization of labile SOC, of which a large part resides in macroaggregates (Elliott, 1986; Gupta and Germida, 1988). Evidence of physical protection of SOC within macroaggregates has been presented from the 34 to 61% greater CO_2–C released from crushed macroaggregates than from intact macroaggregates during laboratory incubations (Elliott, 1986; Gupta and Germida, 1988).

Conservation tillage systems, especially ZT, appear to be promising alternatives to clean cultivation, because conservation tillage systems can abate the loss of organic matter and associated declines in soil quality (Dick, 1983; Rasmussen and Collins, 1991; Elliott et al., 1994). The importance of macroaggregate-associated SOC to soil quality has been demonstrated following conversion of grassland soils to cultivation (Elliott, 1986; Gupta and Germida, 1988). However, limited data are available on whether ZT management on previously cultivated soil provides opportunities for protection of total and active pools of SOC within macroaggregates. In a sandy clay loam from Georgia, mineralizable C from macroaggregates under ZT was 47% greater than under CT at a depth of 0 to 50 mm, but 25% lower at a depth of 50 to 150 mm (Beare et al., 1994a). In addition, greater physical protection of SOC within macroaggregates under ZT than CT was observed at a depth of 0 to 50 mm, but not deeper.

Comparison of SOC concentrations between water-stable aggregate (WSA) classes has led to the identification of macroaggregates as a source of highly enriched SOC (Elliott, 1986; Gupta and Germida, 1988). A particular WSA class may be enriched in SOC, yet constitute a small fraction of the whole soil, which minimizes its impact in a whole-soil evaluation. Standing stock of soil properties within a WSA class should give a better evaluation of both location and relative contribution. In addition, differences in bulk density among management systems can be accounted for in standing stock calculations, which is mass per unit volume.

In the frigid semiarid climate of northwestern Canada,

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Abbreviations: BSR, basal soil respiration; CT, conventional tillage; SMBC, soil microbial biomass carbon; SOC, soil organic carbon; WSA, water-stable aggregate; ZT, zero tillage.

native SOC content tends to be higher and the effect of tillage on SOC content is generally smaller than in mesic and thermic regions of North America (Carter and Rennie, 1982). Therefore, macroaggregate-associated changes in SOC due to tillage regime may also be smaller in this frigid semiarid climate, but remain unknown. In addition, the effect of soil texture within a climatic zone on macroaggregate-associated changes in SOC due to tillage regime deserves investigation in order to better predict the effect of conservation tillage systems on SOC sequestration. Our objectives were to: (i) determine the WSA distribution of standing stocks of active C pools (i.e., SMBC, C mineralization, and macroaggregate-protected SOC), (ii) elucidate the WSA class and soil depth of potential changes in active C pools in response to tillage management, and (iii) characterize the role of soil texture on active C pools within WSA classes.

MATERIALS AND METHODS

Site Characteristics and Crop Management

Soils managed under both CT and ZT were collected from four locations in the Peace River agroecosystem of northern Alberta and British Columbia prior to seeding in late April to early May of 1995. Specific location, soil characteristics, crop management, and experimental design are described in Table 1. Mean annual temperature is 1 to 2°C and mean annual precipitation is 450 to 500 mm. Conventional tillage consisted of one fall tillage with a cultivator equipped with chisels spaced at 200 mm and a working depth of 100 to 150 mm, followed by two cultivations (80–100-mm depth) in the spring prior to seeding. Zero tillage consisted of harrowing following harvest to evenly distribute straw and spraying glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] to control weeds prior to seeding. All crops were sown in mid May with a double-disk press drill in 170-mm-wide rows and harvested in September.

Soil Sampling and Water-Stable Aggregate Fractionation

Soil samples consisted of eight soil cores (25-mm diam.) sectioned into depth increments of 0 to 50, 50 to 125, and 125 to 200 mm. Soil properties of the 0- to 200-mm depth were calculated from the volume and bulk density of each depth section. Cores were collected in the center between rows of the previous crop and equidistantly along a diagonal transect within each plot. Soil was air dried and gently crushed to pass a 5.6-mm screen to remove large stones. Soil bulk density was calculated from the weights of total field-moist soil and an oven-dried subsample (60°C, 48 h) and the volume of the coring tool.

Water-stable aggregate classes were collected from 80 to 100 g of air-dried soil placed on a nest of sieves (175-mm diam.) with openings of 1.0 and 0.25 mm. Soil was quickly immersed in water and the sieves raised and lowered (35-mm stroke length) 160 times during 10 min (Kemper and Rosenau, 1986). Floating organic material retained within the walls of the top sieve was collected using a 0.125-mm screen. After removing sieves, water containing soil that had passed the 0.25-mm screen was poured over a 0.05-mm screen. Soil passing the 0.05-mm screen was allowed to settle for 1 h and pooled across the three depths after decanting. All five WSA classes (i.e., floating, 1.0–5.6, 0.25–1.0, 0.05–0.25, and <0.05 mm) were oven dried (60°C, 24 h).

Soil Biological and Chemical Properties

Carbon mineralization from the 0.05- to 5.6-mm WSA classes was determined from a 5- to 15-g subsample, depending on availability of soil. Soil was placed in a 30-mL beaker in a 1-L canning jar along with vials containing 10 mL of 0.2 *M* NaOH to trap evolved CO_2 and water to maintain high humidity. Soil was moistened to near field capacity, which was determined from water retention curves described previously for each soil (0.25 kg water kg^{-1} for the Donnelly loam, 0.3 kg water kg^{-1} for the Donnelly silt loam and Hythe clay loam, and 0.4 kg water kg^{-1} for the Falher clay). Carbon mineralization from the <0.05-mm WSA class was determined from a 10- to 40-g subsample, which was placed in a 50-mL beaker and moistened with 0.25 kg water kg^{-1}. Carbon mineralization from the floating material was determined from a 0.3-g subsample that was homogenized by grinding to <1 mm and incubated with 3 g of 0.6- to 0.85-mm purified sand and 0.9 mL of water. All WSA classes were incubated at 25°C for 24 d and alkali traps were replaced at 3 and 10 d; the quantity of CO_2–C evolved was determined by titration (Anderson, 1982). Basal soil respiration for each WSA class was estimated as the rate of CO_2–C evolved from 10 to 24 d, since ≥90% of the flush of CO_2–C following rewetting was previously found to occur prior to 10 d (Franzluebbers et al., 1996).

At the end of 24 d, soil was removed from the canning jar, fumigated with chloroform for 24 h, and then reincubated in a canning jar at 25°C for another 10 d. Soil microbial biomass C was calculated from the CO_2–C evolved during 10 d following fumigation, assuming an efficiency factor of 0.41 (Voroney

Table 1. Site and experimental conditions of the four field studies.

Property	Donnelly loam	Donnelly silt loam	Hythe clay loam	Falher clay
Location	55°42′N, 120°10′W	55°46′N, 120°21′W	55°11′N, 119°32′W	55°43′N, 118°41′W
Soil classification (USDA)	coarse-loamy, mixed, frigid Typic Cryoboralf	fine-loamy, mixed, frigid Typic Cryoboralf	fine, montmorillonitic, frigid Mollic Cryoboralf	fine, montmorillonitic, frigid Typic Natriboralf
Soil organic C, kg m^{-2} $[0.2\ m]^{-1}$	4.3	5.1	6.8	8.2
Clay, %, 0–0.2-m depth	18	28	37	63
Silt, %, 0–0.2-m depth	46	51	41	31
pH (1:2 soil/water)	6.6	5.5	6.7	5.7
Initiation of tillage comparison	1988	1979	1991	1989
Crop sequence (previous crop to sampling in 1995 is underlined)	<u>wheat</u>–canola–barley	<u>barley</u>	<u>barley</u>–canola–barley	<u>barley</u>–fallow–canola–wheat
Experimental design	paired plots in adjacent fields	paired plots in adjacent fields	randomized, block	randomized, block
Plot size, m	20 by 50	20 by 50	3 by 15	12 by 39
Replications	4	3	4	4

and Paul, 1984). Soil microbial biomass C of the floating fraction was not determined.

Macroaggregate-protected SOC was calculated as the sum of the difference in C mineralized during 0 to 3, 3 to 10, and 10 to 24 d of incubation between crushed and intact macroaggregate WSA classes. Five- to ten-gram subsamples of large macroaggregates (1.0–5.6 mm) and small macroaggregates (0.25–1.0 mm) were crushed to microaggregate size (<0.25 mm) and incubated as described above. Whole-soil SMBC and C mineralization were determined as described above for WSA classes, except the amount of soil was 40 g for C mineralization and 20 g for SMBC, and fumigation was at 10 d for SMBC. Organic C of all WSA classes and of the whole soil was determined using the modified Mebius method (150°C, 30 min) in digestion tubes (Nelson and Sommers, 1982).

Statistical Analyses

Soil properties of the WSA classes (i.e., SMBC, C mineralized in 24 d, BSR, and macroaggregate-protected SOC) and of the whole soil (i.e., SMBC and C mineralized in 24 d) were analyzed for each soil depth, with tillage regime as a split plot within soil type using the general linear model procedure of SAS (SAS Institute, 1990). Concentrations of SMBC and BSR were analyzed for each soil depth, with tillage regime and WSA class as sources of variation averaged across soil types. In order to separate the effect of clay content on soil biological properties from that of SOC, SMBC and BSR as fractions of SOC were regressed on clay content. Clay content and SOC were highly related ($r = 0.97$, Table 1). Similarly, specific respiratory activity of SMBC was also regressed on clay content in order to identify potential effects of clay content on the quality of organic material mineralized independent of the level of SMBC.

Tillage regime, WSA class, and linear clay content effects on soil properties were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Soil Microbial Biomass Carbon

Soil microbial biomass C concentration was generally greater in both macroaggregate WSA classes than in microaggregates at the 0- to 125-mm depth (Fig. 1). Averaged across soils, SMBC concentration in macroaggregates under CT was 43 and 33% greater than in microaggregates at 0 to 50 and 50 to 125 mm, respectively, while under ZT the corresponding differences were 27 and 17%. However, at a depth of 125 to 200 mm, SMBC concentration was generally lower in macroaggregates than in microaggregates (Fig. 1), averaging 3 and 9% lower under CT and ZT, respectively. Conceptually, the flow of C from roots and residues is from macroaggregates to microaggregates in a hierarchal system (Tisdall and Oades, 1982; Elliott, 1986). Macroaggregates near the soil surface, therefore, appeared to receive more and to subsequently retain a larger percentage of the plant root and residue C as substrate for growth of microbial biomass than at lower depths.

Averaged across soils and tillage regimes, the portion of SOC as SMBC at 0- to 50-mm depth was 20, 15, and 16 g kg^{-1} in large macroaggregates, small macroaggregates, and microaggregates, respectively. No differences between macroaggregates and microaggregates occurred at lower depths. Our results suggested that, when expressed as a portion of SOC, macroaggregates had a greater concentration of SMBC than microaggregates only near the soil surface. Soil microbial biomass C as a portion of SOC was greater in macroaggregates than in microaggregates in a sandy loam (Gupta and Germida, 1988) and lower in macroaggregates than in microaggregates in a silt loam (Seech and Beauchamp, 1988). Reasons for lower SMBC concentration in macroaggregates than in microaggregates in the latter study remain unclear, but may be due to differences in methods of WSA fractionation or SMBC determination.

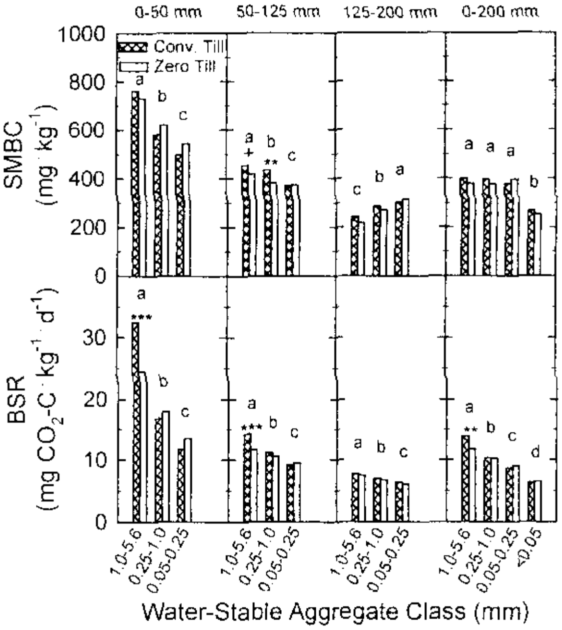

Fig. 1. Soil microbial biomass C (SMBC) concentration and basal soil respiration (BSR) rate of water-stable aggregate (WSA) classes as affected by soil depth and tillage regime averaged across four soils. WSA classes averaged across tillage regimes within a soil depth with the same letter above bars are not significantly different at $P \leq 0.1$. Within a soil depth and WSA class, †, **, and * above bars indicate significance between tillage regimes at $P \leq 0.1$, 0.01, and 0.001, respectively. SMBC and BSR of the <0.05-mm class were determined only for the 0- to 200-mm depth.**

The portion of SOC as SMBC in large macroaggregates was lower under ZT than under CT in coarse-textured soils (Table 2). To a depth of 200 mm, SMBC concentration of macroaggregates under ZT was lower than under CT in the Donnelly loam and Donnelly silt loam, but greater than under CT in the Falher clay, primarily due to differences that developed near the soil surface (data not shown). The interaction between tillage regime and clay content on macroaggregate-associated SMBC may be due to: (i) the greater role of crop residue contact with soil particles for enhancing aggregation and microbial biomass and activity in soils with low clay content, (ii) the lower native aggregation in coarse-textured soils, or (iii) the varying strength of macroaggregate binding agents as a result of clay content, which allowed SMBC to associate with different WSA classes.

Standing stock of SMBC in macroaggregates of the loam and silt loam was lower than or equal to the standing stock of SMBC in microaggregates (Table 3). Stand-

Table 2. Portion of soil organic C (SOC) as soil microbial biomass C (SMBC), portion of SOC as basal soil respiration (BSR), and specific respiratory activity of SMBC within water-stable aggregate classes and whole soil as a function of clay content (%) and tillage regime.

Water-stable aggregate class (mm)	Conventional tillage		Zero tillage	
	β_0‡	β_1	β_0	β_1
Portion of soil organic C as microbial biomass, g SMBC kg^{-1} SOC				
1.0 to 5.6	19.8***	−0.10**	15.3***	−0.03
0.25 to 1.0	13.8***	−0.02	13.7***	−0.02
0.05 to 0.25	*19.5****	*−0.11****	*19.4****	*−0.09***
<0.05§	21.2***	−0.17†	23.4***	−0.22†
Whole soil	43.2***	−0.29***	41.8***	−0.28***
Portion of soil organic C as basal soil respiration, g BSR-C kg^{-1} SOC d^{-1}				
Floating§	3.02***	0.005	2.69***	0.000
1.0 to 5.6	0.84***	−0.007**	0.51***	−0.002
0.25 to 1.0	0.39***	−0.002†	0.40***	−0.002†
0.05 to 0.25	0.45***	−0.002***	0.50***	−0.004***
<0.05§	0.55***	−0.005**	0.63***	−0.006**
Whole soil	1.22***	−0.014***	0.84***	−0.009***
Specific respiratory activity, mg BSR-C kg^{-1} SMBC d^{-1}				
1.0 to 5.6	41.7***	−0.16	34.7***	0.06
0.25 to 1.0	29.0***	−0.05	30.1***	−0.07
0.05 to 0.25	*22.5****	*0.03*	*26.0****	−0.07
<0.05§	29.0***	−0.14†	29.2***	−0.10
Whole soil	28.9***	−0.25**	21.0***	−0.14†

†,**, and *** Coefficients significantly different from zero at $P \leq 0.1$, 0.01, and 0.001, respectively.
‡ β_0 is the intercept and β_1, is the slope.
§ Equations were developed from the 0- to 200-mm depth only (n = 15), whereas equations for other WSA classes and whole soil were developed from the 0- to 50-, 50- to 125-, and 125- to 200-mm depths (n = 45).

ing stock of SMBC in macroaggregates of fine-textured soils was severalfold greater than in macroaggregates of coarse-textured soil (Table 3), due to large differences in WSA distribution (Franzluebbers and Arshad, 1996). Standing stock of SMBC at 0- to 200-mm depth was greatest in microaggregates of the Donnelly loam, was evenly distributed among the four WSA classes of the Donnelly silt loam and Hythe clay loam, and was greatest in large macroaggregates of the Falher clay (Table 4). Increasing standing stock of SMBC in macroaggregates with increasing SOC and/or clay content indicates important interactions between soil physical, chemical, and biological properties in determining the size and location of active pools of SOC.

Averaged across soils, ZT increased the standing stock of SMBC in macroaggregates compared with CT mostly at a depth of 0 to 50 mm (Table 3). This was a result of greater macroaggregation under ZT than under CT, despite similar SMBC concentrations between tillage regimes. In microaggregates, the standing stock of SMBC under ZT was similar or lower than under CT below a depth of 50 mm. Standing stock of SMBC incorporated the effects of WSA distribution and concentration of SMBC for quantification on a whole-soil basis.

Whole-soil SMBC averaged 101 ± 6 g m^{-2} greater than the sum of the four WSA classes (Table 4). Several explanations are likely to account for this large discrepancy. Soil microbial biomass C of the floating material was not determined, but may have contributed significantly to total SMBC, since C mineralized in 24 d from the floating material was 13 to 41% of whole-soil C mineralization (Table 4). Secondly, soluble C substrates

Table 3. Soil microbial biomass C of water-stable aggregate (WSA) classes as affected by soil type, depth, and tillage regime (CT is conventional tillage and ZT is zero tillage).

Soil type	0–50-mm depth CT	ZT	50–125-mm depth CT	ZT	125–200-mm depth CT	ZT
	g m^{-2}					
	1.0 to 5.6 mm WSA class					
Donnelly loam	2.1 ***	2.8	2.1	3.1	2.4	2.3
Donnelly silt loam	6.7	6.0	13.2	13.4	7.4 †	5.3
Hythe clay loam	6.4 ***	8.5	9.6	10.5	6.0	5.0
Falher clay	8.1 ***	10.6	14.3	15.4	9.7 ***	12.6
Mean	5.8 ***	7.0	9.8	10.6	6.4	6.3
	0.25 to 1.0 mm WSA class					
Donnelly loam	2.8	4.0	4.1	5.5	2.9	3.4
Donnelly silt loam	5.8	7.2	10.1	11.0	8.8 †	9.7
Hythe clay loam	8.0 **	10.3	13.7	13.4	11.3	10.9
Falher clay	9.5	8.6	8.8	8.1	7.7 **	8.9
Mean	6.5	7.5	9.2	9.5	7.7 *	8.2
	0.05 to 0.25 mm WSA class					
Donnelly loam	7.2	6.3	11.5 †	9.4	9.6	9.7
Donnelly silt loam	11.6 **	7.6	11.4 *	7.8	8.8	6.8
Hythe clay loam	11.6 **	14.7	14.8	15.3	8.5	7.0
Falher clay	8.3 *	10.4	5.9	6.5	4.1	5.2
Mean	*9.7*	*9.8*	*10.9 †*	*9.8*	*7.8*	*7.2*

†,*,**, and *** between tillage means within soil depth and WSA class indicate significance at $P \leq 0.1$, 0.05, 0.01, and 0.001, respectively.

and microorganisms may have been washed out of the soil during the wet-sieving procedure. Thirdly, SMBC was determined from WSA classes following fumigation at 24 d, rather than at 10 d as for the whole soil, which may have decreased the supply of substrates for maintaining SMBC. Fumigation of soil at 35 d rather than at 13 d of incubation resulted in 5 and 7% lower SMBC in a sandy loam and clay soil, respectively (Ocio and Brookes, 1990). In a silty clay loam with five levels of SOC, fumigation at 15 d rather than at 3 d resulted in 12 ± 19% lower SMBC (Franzluebbers et al., 1996).

Carbon Mineralization

Basal soil respiration generally decreased with decreasing size of WSA class, especially at a depth of 0 to 50 mm (Fig. 1). Differences in BSR among WSA classes were smaller, but significant at lower depths. Basal soil respiration decreased with soil depth, similar to the decrease in SMBC with soil depth. Within WSA classes, BSR was related to both SOC (r^2 of 0.30–0.63) and SMBC (r^2 of 0.64–0.74). Close relationships between active and total soil C pools have been reported previously and are due to the linkage of potential microbial activity with available substrates (Franzluebbers et al., 1994).

Basal soil respiration as a portion of SOC in the floating material was four to 14 times greater than in other WSA classes (Table 2). Greater respiratory activity from this organic material than other WSA classes suggests that it plays an important role in nutrient cycling and in supplying substrate for microbial processes that lead to structural stability. Floating material was probably composed of undecomposed and partially decomposed crop roots and residues (Cambardella and Elliott, 1992) and is, perhaps, more likely comparable to the light-density fraction of SOC found in Dutch grassland soils,

Table 4. Soil microbial biomass C and C mineralized in 24 d from water-stable aggregate classes and the portion of soil organic C as macroaggregate-protected C to a depth of 200 mm as affected by soil type and tillage regime (CT is conventional tillage and ZT is zero tillage).

Water-stable aggregate class	Donnelly loam			Donnelly silt loam			Hythe clay loam			Falher clay		
	CT		ZT	CT		ZT	CT		ZT	CT		ZT
	Soil microbial biomass C, $g\ m^{-2}$											
1.0 to 5.6	6.7		8.2	27.8		24.7	22.7		24.4	32.6	*	39.5
0.25 to 1.0	9.9		13.0	24.9		28.0	33.3		34.9	26.0		25.8
0.05 to 0.25	28.2		25.5	31.1	*	21.8	33.9		35.9	18.0		21.4
<0.05	10.8		9.6	13.2		11.6	6.8		6.7	8.5		8.5
LSD ($P \leq 0.05$)	3.9		5.5	3.6		12.8	7.8		5.1	4.2		10.1
Sum of parts	55.5		56.3	97.0	†	86.1	96.7	†	102.0	85.1	*	95.1
Whole soil	154.7		158.5	195.6		179.2	194.8		200.2	197.3		209.6
	C mineralized in 24 d, $g\ m^{-2}$											
Floating	36.5		31.5	30.2		25.1	33.2	***	16.2	11.4		14.0
1.0 to 5.6	9.8		11.6	38.8		33.6	29.8		29.3	39.9	*	46.6
0.25 to 1.0	12.5		15.9	27.1		34.3	31.5		35.9	27.0		26.5
0.05 to 0.25	28.0		24.5	28.8		21.8	30.6		34.1	17.8		18.2
<0.05	9.9		9.0	11.7		9.4	8.3		9.4	6.1		6.3
LSD ($P \leq 0.05$)	3.6		7.9	7.8		12.4	10.9		3.8	4.7		7.0
Sum of parts	96.8		92.5	136.6		124.1	133.4		124.9	102.3		111.6
Whole soil	100.9	*	76.9	128.9	*	107.9	126.4		113.0	89.9		90.6
	Portion of soil organic C as macroaggregate-protected C, $g\ kg^{-1}$ SOC											
1.0 to 5.6	6.3		8.5	2.0		1.9	1.0		2.7	0.6		1.8
0.25 to 1.0	4.8		5.3	2.7		2.3	3.3		3.0	1.0		1.5
0.25 to 5.6	5.1		6.5	2.3		2.0	2.5		2.9	0.8		1.7

†,*,**, and *** between tillage means within soil type and WSA class indicate significance at $P \leq 0.1$, 0.05, 0.01, and 0.001, respectively.

which had severalfold greater specific C mineralization than heavy-density fractions or whole soil (Hassink, 1995).

Large macroaggregates had greater basal soil respiration as a portion of SOC than microaggregates, regardless of soil texture under CT and only in fine-textured soil under ZT (Table 2). Both macroaggregate classes also had greater specific respiratory activity of SMBC than microaggregates, regardless of soil texture and tillage regime (Table 2). The conceptual model presented by Elliott (1986) suggesting that organic matter in macroaggregates is more labile than in microaggregates was supported by our results for large macroaggregates, but not for small macroaggregates using BSR as a portion of SOC.

Basal soil respiration as a portion of SOC decreased with increasing clay content in whole soil and in all WSA classes, except in the floating material (Table 2). These results suggest that potential turnover of SOC was greater in coarse-textured soils than in fine-textured soils and are in agreement with those of previous studies evaluating textural effects on SOC turnover (van Veen et al., 1985; van Gestel et al., 1991; Hassink et al., 1993). Greater SOC turnover in coarse-textured soils may be due to greater protection of SOC by clay adhesion and inter- and intraaggregate isolation in fine-textured soils (Rutherford and Juma, 1992; Hassink et al., 1993).

Basal soil respiration as a portion of SOC in whole soil was greater under CT than under ZT in coarse-textured soil, which appeared to be a contribution from floating material and large macroaggregates, but not from other WSA classes (Table 2). When calculated in the same manner, BSR as a portion of SOC in a sandy clay loam from Georgia at a depth of 0 to 150 mm averaged 0.48 g BSR-C kg^{-1} SOC d^{-1} in macroaggregates and 0.40 g BSR-C kg^{-1} SOC d^{-1} in microaggregates (Beare et al., 1994a,b). Macroaggregates also had a greater portion of SOC as BSR than microaggregates in a sandy loam and a silt loam (0.65 ± 0.25 vs. 0.50 ± 0.13 g BSR-C kg^{-1} SOC d^{-1}) (Elliott, 1986; Gupta and Germida, 1988).

Standing stock of C mineralized in 24 d of incubation was generally greater in the sum of the two macroaggregate classes than in microaggregates, except in the Donnelly loam under CT (Table 5), similar to our observations for SMBC. Carbon mineralized in 24 d was greater under ZT than under CT only in small macroaggregates at a depth of 0 to 125 mm. To a depth of 200 mm, major contributions to standing stock of C mineralized in 24 d shifted from the floating and microaggregate classes in coarse-textured soil to macroaggregate classes in fine-textured soil (Table 4). The floating fraction accounted for 22 ± 10% (mean of the eight soil–tillage combinations ± standard deviation among combinations) of the total C mineralized, with decreasing contribution with increasing clay content. Although we did not measure N mineralization, it has been shown to increase with the quantity of light-fraction SOC (Janzen, 1987). Therefore, soil textural and tillage-induced changes in aggregation altered the location of active soil C pools, which have important implications on the in situ turnover of C and N.

The sum of C mineralized in 24 d from the WSA classes was greater than that determined from whole soil in the Donnelly silt loam under ZT and in the Falher clay under both tillage regimes (Table 4), but not different in the remaining five comparisons. Greater C mineralization from fractionated soil than from whole soil, especially in fine-textured soil, may have been due to greater exposure of C substrates to microorganisms as a result of (i) disruption of some meta-stable macroaggregates during physical fractionation and (ii) less

Table 5. Carbon mineralized in 24 d from water-stable aggregate (WSA) classes as affected by soil type, depth, and tillage regime (*CT is conventional tillage and ZT is zero tillage*).

	0–50-mm depth			50–125-mm depth			125–200-mm depth		
Soil type	CT		ZT	CT		ZT	CT		ZT
	g CO_2–C m^{-2}								
	1.0 to 5.6 mm WSA class								
Donnelly loam	4.1		4.1	2.9		4.6	2.7		3.0
Donnelly silt loam	10.8		9.1	15.1		16.3	12.3	**	8.1
Hythe clay loam	8.9		9.4	11.7		11.5	8.3		7.8
Falher clay	11.8	*	14.0	17.1		16.7	10.5	***	14.9
Mean	8.9		9.2	11.7		12.3	8.4		8.5
	0.25 to 1.0 mm WSA class								
Donnelly loam	3.8	†	5.2	4.6		5.6	3.9		4.9
Donnelly silt loam	8.3	†	10.0	10.9	*	14.5	7.8		9.6
Hythe clay loam	8.0	**	10.4	13.2		15.2	10.1		10.0
Falher clay	8.2		8.1	10.4		9.4	8.3		8.8
Mean	7.1	**	8.4	9.8	*	11.2	7.5		8.3
	0.05 to 0.25 mm WSA class								
Donnelly loam	9.0		8.1	11.8	†	9.4	7.4		6.9
Donnelly silt loam	11.4	*	8.2	11.5	†	8.8	6.4		5.2
Hythe clay loam	10.4	*	13.3	14.0		16.0	7.1	†	5.6
Falher clay	7.3		8.2	6.8		6.6	4.0		4.1
Mean	9.5		9.5	11.0		10.2	6.2	†	5.5

†, *, **, *and* *** *between tillage means within soil depth* and WSA class indicate significance at $P \leq 0.1$, 0.05, 0.01, and 0.001, respectively.

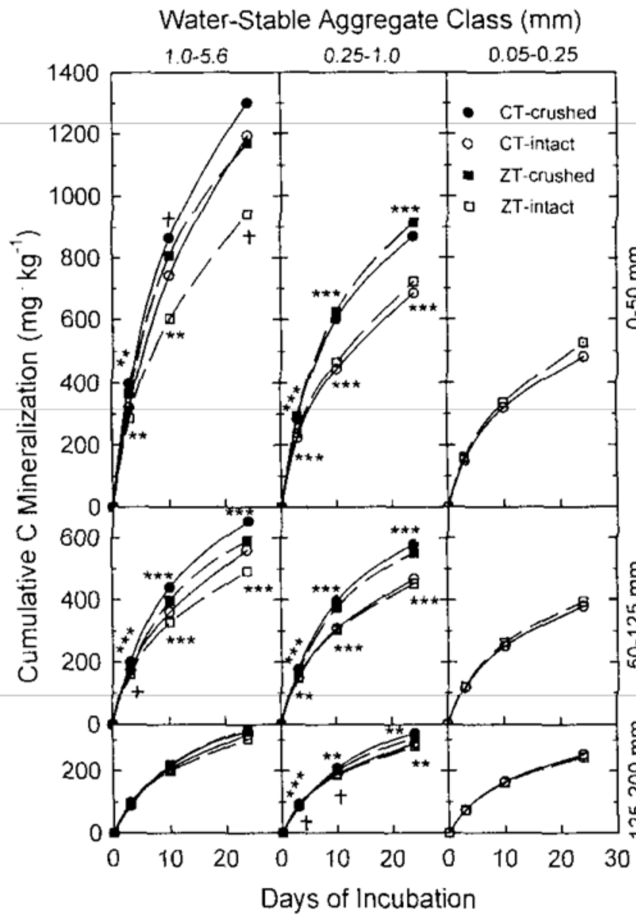

Fig. 2. Carbon mineralized in 24 d from intact and crushed (<0.25 mm) water-stable aggregates (WSA) averaged across four soils as affected by soil depth and tillage regime. CT is conventional tillage and ZT is zero tillage. †, **, *and* * *denote significant differences* between intact and crushed WSA at $P \leq 0.1$, 0.01, and 0.001, respectively.**

protection from clay at the interface of different-sized aggregates.

Macroaggregate-Protected Soil Organic Carbon

Carbon mineralization from crushed macroaggregates when averaged across soils decreased with soil depth and decreasing size of WSA class, similar to that observed for intact aggregates (Fig. 2). During the first 3 d following rewetting of the crushed macroaggregates, 28 ± 17% (mean of the eight soil–tillage combinations ± standard deviation among combinations) of the physically protected SOC was mineralized, while 58 ± 7% was mineralized from 3 to 10 d of incubation. Rapid mineralization of substrates made available after crushing indicates that the macroaggregate-protected SOC was highly labile and probably originated from microbial biomass and microbially derived decomposition products entrapped within macroaggregates.

The portion of total C mineralized in 24 d from crushed macroaggregates as macroaggregate-protected SOC to a depth of 200 mm averaged 15 ± 9% (mean of the eight soil–tillage combinations ± standard deviation among combinations), decreasing with increasing clay and SOC contents. The portions within large macroaggregates averaged 14, 13, and 2% and within small macroaggregates averaged 22, 18, and 7% at depths of 0 to 50, 50 to 125, and 125 to 200 mm, respectively. A greater portion of protected SOC in small than in large macroaggregates, along with a lower portion of SOC as BSR in smaller macroaggregates (similar to that in microaggregates), would indicate that only larger macroaggregates contained more unprotected, labile C substrates than those of microaggregates, as suggested by Elliott (1986). The portions of total mineralized C released by crushing macroaggregates in our study were similar to those found in cultivated soil (5–16%) and in native grassland soil (4–13%) (Elliott, 1986; Gupta and Germida, 1988).

Protected SOC in large macroaggregates as a percentage of total C mineralized in 24 d averaged 4 and 19% at 0- to 50-mm depth, 14 and 18% at 50- to 125-mm depth, and 3 and 7% at 125- to 200-mm depth under CT and ZT, respectively. Protection of SOC in small macroaggregates was similar between tillage regimes. Similarly, Beare et al. (1994a) reported greater macroaggregate-protected SOC under ZT than under CT. The increase in macroaggregate-protected SOC with ZT compared with CT near the soil surface implies not only a strong linkage between microbial activity and crop residue placement on aggregation, but also greater physical protection of SOC within those aggregates. A trend for a greater fraction of macroaggregate-protected SOC with ZT than with CT at lower soil depths suggests that reduced soil disturbance or alterations in root distribution with ZT may further contribute to protection of SOC.

Zero tillage increased the standing stock of macroaggregate-protected SOC compared with CT mostly at the soil surface (Table 6). To a depth of 200 mm, the stand-

Table 6. Macroaggregate-protected soil organic C as affected by water-stable aggregate (WSA) class, soil type, depth, and tillage regime (CT is conventional tillage and ZT is zero tillage).

Soil type	0–50-mm depth CT		0–50-mm depth ZT	50–125-mm depth CT		50–125-mm depth ZT	125–200-mm depth CT		125–200-mm depth ZT	0–200-mm depth CT		0–200-mm depth ZT
	g m^{-2}											
1.0 to 5.6 mm WSA class												
Donnelly loam	0.3		1.5	1.6		2.0	0.6	†	2.1	2.5		5.6
Donnelly silt loam	0.5		1.2	2.5		1.8	−0.1		−0.1	2.9		2.8
Hythe clay loam	1.0		2.4	0.9	†	2.6	−0.7		−0.6	1.2		4.4
Falher clay	1.2		3.1	0.1	*	2.2	0.2		−0.3	1.5		5.0
Mean	0.7		2.0	1.3	†	2.1	0.0		0.3	2.0	*	4.5
0.25 to 1.0 mm WSA class												
Donnelly loam	1.3		1.5	2.0		2.9	1.6		1.9	4.9		6.2
Donnelly silt loam	1.6		1.6	1.2		1.2	1.2		1.4	4.0		4.1
Hythe clay loam	3.2		3.8	4.2		4.1	0.1		−0.1	7.4		7.8
Falher clay	1.7	†	2.4	1.3		1.2	−0.4		−0.4	2.6		3.3
Mean	1.9	†	2.3	2.2		2.4	0.6		0.7	4.7		5.4
0.25 to 5.6 mm WSA class												
Donnelly loam	1.6		3.0	3.6		4.9	2.2	†	4.0	7.4		11.9
Donnelly silt loam	2.1		2.8	3.7		3.0	1.0		1.2	6.8		7.0
Hythe clay loam	4.2		6.2	5.0		6.7	−0.6		−0.7	8.6		12.2
Falher clay	2.8		5.5	1.4		3.4	−0.2		−0.6	4.1	†	8.3
Mean	2.7		4.4	3.5		4.5	0.6		1.0	6.7	*	9.8

† and * between tillage means within soil depth and WSA class indicate significance at $P \leq 0.1$ and 0.05, respectively.

ing stock of macroaggregate-protected SOC averaged 46% greater under ZT than under CT, indicating that ZT may indeed play a large role in protecting SOC by entrapment of potentially labile C in macroaggregates that would otherwise be subject to easy disruption with tillage.

Fine-textured soils sequestered more macroaggregate-protected SOC near the soil surface than coarse-textured soils (Table 6), due largely to greater macroaggregation (Franzluebbers and Arshad, 1996). However, to a depth of 200 mm, the portion of SOC as macroaggregate-protected C decreased with increasing clay content and was not different between tillage regimes (Table 4). Beare et al. (1994a) found that the portion of SOC that was protected by macroaggregates averaged 3.5 and 5.9 g kg^{-1} SOC under CT and ZT, respectively. The potential of ZT to increase the portion of SOC as macroaggregate-protected SOC in soils of northern Alberta–British Columbia may have been limited by the frigid, semiarid climate compared with the thermic, humid climate of Georgia.

SUMMARY AND CONCLUSIONS

Macroaggregates of soils ranging in texture from a loam to a clay in northern Alberta and British Columbia had a greater concentration of SMBC and mineralizable C than microaggregates near the soil surface, but more similar concentrations of these active C pools at lower depths. Concentration of macroaggregate-protected SOC was also greatest near the soil surface and decreased with depth. Insignificant and sometimes negative changes in SOC, SMBC, BSR, and C mineralized in 24 d with ZT, compared with CT in whole soil, are in contrast with other studies in mesic and thermic regions where positive influences of ZT on active pools of C have been reported. However, we observed a redistribution of active C pools within WSA classes, suggesting that active C pools become more associated with macroaggregates under ZT and with microaggregates under CT. Soil microbial biomass C, BSR, and C mineralized in 24 d were greater under ZT than under CT in macroaggregates, especially near the surface, and lower under ZT than under CT in microaggregates, especially at lower depths. Soil under ZT contained more macroaggregate-protected SOC than under CT, indicating that reduced soil disturbance could lead to greater SOC sequestration and improved soil quality with improvements in macroaggregation.

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